

## Overview of NASA's Electric Propulsion Program

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NASA's Office of Advanced Concepts and Technology sponsors a coordinated program to develop electric propulsion technologies applicable to a broad range of future missions. Near-term hydrazine arcjet research is focused on increasing the specific impulse from the 5,000 m/s level currently used on the TelStar 401 satellite to 6,000 m/s. Injection of xenon ion thruster technology, based on a light-weight, 30-cm-diameter thruster, is being accomplished through a program designed to validate this technology for flight application. The projected needs of future, ambitious Earth-orbital and solar system exploration missions are being addressed through research on C60-fueled ion engines, lithium-fueled electromagnetic engines, and system studies of nuclear electric propulsion vehicles.

### Introduction

Recognizing that on-board propulsion is essential for both commercial and government spacecraft, NASA's Office of Advanced Concepts and Technology (OACT) sponsors an extensive effort to develop high-performance propulsion technology to enhance near- and fm-term U.S. space missions. On-board propulsion applications include orbit circularization (apogee motors), north-south station keeping (NSSK) for geosynchronous Earth orbit (GEO) spacecraft, orbit control, orbit repositioning and deep space delta-V requirements [1]. The program, which is being conducted through the NASA Lewis Research Center and the Jet Propulsion Laboratory, includes research on electrothermal, electrostatic and electromagnetic propulsion technologies covering a wide range of potential applications.

On-board propulsion can take up a large fraction of the initial spacecraft mass, especially for "difficult" solar system exploration missions such as comet and asteroid rendezvous. Because of their high specific impulse capabilities, electric propulsion systems offer large potential improvements in over chemical systems for certain missions. For deep space missions these improvements include the potential to use a smaller launch vehicle, reduced trip times and/or increased delivered mass capability. For near-Earth-space missions, the reduced propulsion system wc4 mass for NSSK or orbit repositioning can be used to increase the

spacecraft life, increase the payload mass, increase the number or speed of repositioning maneuvers, or download the spacecraft to a smaller launch vehicle. For Earth-orbit transfer missions electric propulsion offers the potential for large payload delivery capability using smaller launch vehicles.

The objectives of the program are to develop innovative, high-performance electric propulsion systems and to provide critical services to the user community. The program is structured to include a broad spectrum of activities from fundamental research to specific efforts aimed at technology insertion as indicated in Fig. 1. The principal

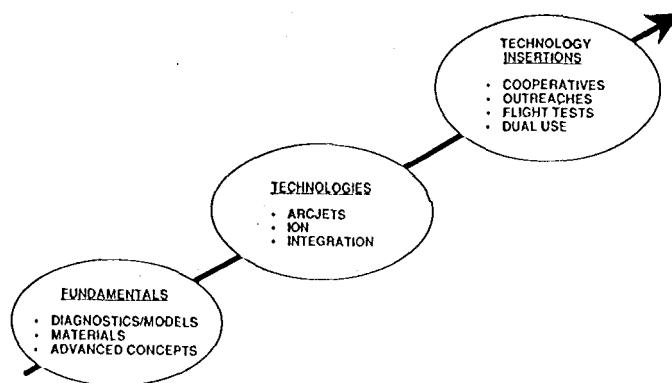


Fig. 1 Scope of NASA's electric propulsion program.

focus of NASA's electric and advanced propulsion technology programs include **development** of high-performance **arcjets**, improving ion thruster life, validation and insertion of ion thruster technology, fundamental research on high-current electromagnetic thrusters and carbon-60 ion thrusters, **verification** of Russian Hall thruster technology (stationary plasma thrusters and anode **layer** thrusters, with primary support from the Ballistic Missile **Defense** Organization), and evaluation of nuclear electric propulsion concepts for **far-term** solar system

### Electrothermal Thrusters

#### Resistojets

**Resistojets** offer the **advantages** of specific impulses at or beyond traditional on-board chemical propulsion while enabling the ability to **utilize** a wide **range** of propellants. **Sub-kilowatt resistojets** have already been flown to provide NSSK on commercial **communication** satellites [2,3]. Several studies in the late 1980s showed the benefits of **waste-gas** and/or water **resistojets** in reducing the propellant resupply for large space systems such as the Spare Station [4-12]. As a result, a program was initiated at NASA **LeRC** to demonstrate the technology for a water **resistojet vaporizer** that can reliably operate with stable phase separation in a **microgravity environment**. **Cyclic endurance** testing of a sand-packed, attitude **insensitive vaporizer** is currently underway [13].

#### Arcjets

The NASA kilowatt-class **arcjet** program was initiated in 1983 in cooperation with industry [14]. This **joint** program led to a first generation **hydrazine arcjet** with a nominal input of 1.8 kW and a specific impulse of approximately 5,000 m/s. Propulsion systems using this thruster **have been baselined** for NSSK on four satellite series: **Telstar 4**, **Intelsat 8**, **Echostar**, and **Asiasat**. The acceptance of **these arcjet** systems has led to calls for higher **performance arcjets**. Advanced **refractory** materials with improved **high-temperature** strength appear to be **necessary** to increase specific impulse levels up to 6,000 m/s with **adequate engine life** [15]. Start-up damage problems in high performance **arcjets** are being addressed through two approaches a "soft-start" technique which limits start-up current **transients**; and a pressure pulse technique designed to **reduce** the time required to achieve steady-state current levels [16]. In addition, new small spacecraft initiatives have **fueled** the demand for **sub-kilowatt hydrazine arcjet development** [17, 18].

For future high power applications, NASA has continued to work on the **development** of 10- to 30-kW hydrogen **arcjets**. This **work is motivated** in part by industry interest in electric orbit transfer. Earlier NASA work on **high-power arcjets** focused on constricted-arc designs and the **development** of a 10-kW power processor unit [19-21]. More **recently work** has concentrated primarily on the evaluation of chambered-arc devices similar to those **tested** by the Giannini Scientific Company in the 1960s. Both **radiatively-** and **regeneratively-cooled** thrusters are currently being evaluated

to **characterize the performance** limitations of these devices [22].

### Plume Characterizations

Molecular computational fluid dynamic (MCFD) models of the **plume** from small **rockets** are being **developed** to provide more accurate analytical tools for the study of rarefied, **low-density** flows. This **effort**, motivated by the need to develop a better understanding of plume effects on spacecraft **surfaces** and systems, includes both **computer code development** and synergistic experimentation. Three numerical **methods**, Navier-Stokes, **Boltzmann**, and **direct-simulation Monte Carlo (DSMC)** have been used in the MCFD program [23-27]. A typical comparison of **calculated** axial velocities obtained from **these** three approaches is shown in Fig. 2.

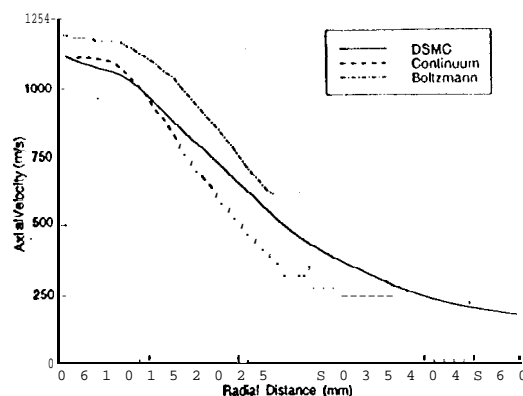


Fig. 2 Comparison of rocket flow field model calculations (12 mm from nozzle exit plane)

### Electrostatic Thrusters

#### Ion Thrusters

**Gridded** ion thrusters can provide high specific impulses (15,000 to 100,000 m/s) at high **efficiency** and so can significantly benefit a number of mission classes including NSSK at **GEO**, orbit repositioning, orbit transfer, and **planetary** exploration missions [28-32]. For deep-spm, small body rendezvous missions (**such as to** asteroids or comets), ion propulsion can reduce the trip time by typically a factor of two while simultaneously increasing the delivered mass to the **target** relative to chemical-ballistic **trajectories** using the same launch vehicle. Similarly, orbit repositioning maneuvers in Earth-orbit can be accomplished **either faster** or more frequently using ion propulsion than chemical propulsion systems.

NASA is addressing both auxiliary and primary propulsion applications of ion propulsion to **cover** a broad range of missions. The principal focus of the near-term ion thruster work is on the development and technology validation of a 30-cm **diameter** xenon ion thruster operated in a "derated" mode. The thruster input power is **derated** from its design value of > 5 kW to a maximum of 2.3 kW in order

to greatly mitigate the known life limiting processes. In addition, the large ion current handling capability of the 30-cm diameter accelerator system enables operation at higher thrust-to-power ratios than smaller ion thrusters reducing ground qualification testing requirements for NSSK applications [33-36].

Three engineering model thrusters (EMT) are currently being fabricated at NASA LeRC for use in the NASA SEP Technology Applications Readiness (NSTAR) program. This program is designed to validate ion propulsion technology for use on commercial and U.S. government spacecraft. The recently fabricated EMT has a mass of approximately 7 kg (Fig. 3) and can be operated over an input power range of 0.55 to 2.3 kW. The NSTAR program will address the service life capability of the engine and characterize its performance and compatibility with the host spacecraft.

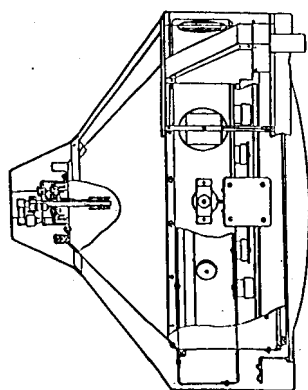


Fig. 3 Cross-sectional schematic of the 30-cm-diameter, low-mass ion thruster for NSTAR.

The NSTAR ion engine service life capability will be established through a combination of long duration testing and the application of probabilistic physics of failure modeling. This combination is the most cost effective approach to establishing the failure risk from damage-accumulation failure modes. The principal failure mode is believed to be due to charge-exchange erosion of the accelerator grid of the two-grid ion accelerator system. A two-grid accelerator system was intentionally tested to failure in an accelerated erosion test in order to establish the behavior of the erosion patterns over time [37]. These data were incorporated into a probabilistic model which can be used to assess the engine failure risk as a function of operating time [38]. Complementary grid erosion modeling is also in progress at ERC, Inc., where a fully 3-D Particle-in-cell code has been developed to predict the erosion pattern and ultimately the erosion rates in ion accelerator systems.

The NSTAR program will also develop an advanced power processor unit (PPU) for the 30-cm engine. For a 2.5 kW maximum input power the PPU specific mass is projected to be approximately 5 kg/kW with an overall efficiency of 0.92 [39].

Recent emphasis on the use of small spacecraft and small launch vehicles for planetary missions [40] has led JPL to scale down the existing 30-cm low-mass ion thruster to a 15-cm diameter size which may facilitate integration onto small spacecraft. The 15-cm thruster, which has a modified ring-cusp discharge chamber design and has been operated at up to 1.1 kW, will also be used as a test-bed for the development of advanced ion accelerator systems [41].

For gridded ion thrusters, the performance and engine life are largely dictated by the performance and life of the ion accelerator system. NASA is pursuing the development of advanced accelerator systems which promise to significantly increase the grid life and current density handling capability relative to state-of-the-art molybdenum grids. This work includes the development of carbon-carbon grids [42-44], diamond matings for molybdenum grids, free standing diamond grids, and the three-grid SAND (Screen, Accelerator, Negative Decelerator) optics configuration [45]. The SAND optics have demonstrated the ability to significantly reduce erosion of the accelerator grid in the central, high-current density region of the accelerator system even at elevated vacuum chamber pressures. This capability enables ion thruster endurance testing to be performed in smaller, less expensive vacuum chambers with modest pumping speeds and should facilitate industry acceptance of ion propulsion technology.

For solar-powered planetary exploration missions NASA is evaluating the benefits of the segmented ion engine design [28]. A segmented engine fabricated at JPL consists of four 15-cm diameter ion sources integrated into a 30-cm equivalent thruster. The 4x15-cm segmented thruster has the same active beam area as the 30-cm thruster, and is approximately the same mass and physical size (Fig. 4), and operates from a single PPU. The potential advantage of this approach is that for missions in which deep engine power throttling is required (such as most SEP planetary missions), gross throttling of the segmented engine is accomplished

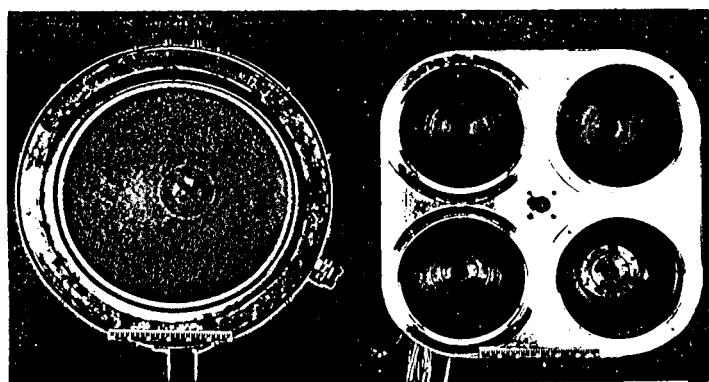


Fig. 4 Segmented ion engine (right) pictured with conventional 30-cm-diameter lab-model thruster (left).

through shutting off individual ion sources (or segments). Since the non-operating ion sources are no longer subject to erosion, the component service life required for a given mission can be significantly reduced relative to the 30-cm thruster.

#### Plasma Contractors

A direct spin-off of the ion propulsion technology program is the development of plasma contractors for use on the Space Station to ground the Station to the ambient space plasma. The Space Station plasma contractor is based on hollow cathode technology developed in the 30-cm ion thruster program. Several cathode and cathode-heater tests are currently underway to demonstrate technology readiness for this application. A long-duration cathode test has now accumulated more than 9,000-hours of operation at an emission current of 12 A.

#### Hall Thrusters

NASA is assisting in the BMDO sponsored program to evaluate Russian Hall thruster technology [46-50]. Thrusters under evaluation include the stationary plasma thruster, SPT-100, and advanced technology stationary plasma thruster, T-100, and the 1.4-kW thruster with anode layer (TAL), D-55. An on-going endurance test of the SPT-100 has accumulated more than 4,500 on/off cycles and 3,500 hours of operation.

#### C<sub>60</sub> Ion Thrusters

Feasibility tests of a C<sub>60</sub>-fueled ion thruster are being performed to evaluate the potential for significantly increasing ion thruster performance at low specific impulses 15,000 to 25,000 m/s [51]. Preliminary results obtained with a direct-current ion source indicate that C<sub>60</sub> can be ionized by electron-impact without fragmenting the molecule. Based on this encouraging result a radio-frequency ion source has been fabricated and will be tested with C<sub>60</sub> in the near future.

#### Electromagnetic Thrusters

##### Magnetoplasmadynamic (MPD) Thrusters

The MPD thruster offers the potential to provide a possibly unique combination of high thrust level and high specific impulse in a compact package. Such capabilities would be attractive for outer planet exploration missions, as well as cargo and piloted planetary missions. Over the past several years many organizations have supported the MPD thruster development program [52,53]. Changing emphasis at NASA to smaller, lower power missions, however, has resulted in a descoping of the MPD thruster development program. Current efforts now center on the evaluation of 100-kW class, lithium-fueled MPD thrusters in a cooperative program with the Moscow Aviation Institute in Russia, and on the development of long-life, high-current cathodes [54,55]. A dedicated, high-current cathode test facility has been completed and preliminary thermal measurements made

in this facility agree well with the predictions of a cathode thermal model developed under this program (Fig. 5) [56]. The goal of the cathode program is to increase the demonstrated charge transfer capability of existing cathodes by two orders of magnitude (from 10<sup>5</sup> A-hours to 10<sup>7</sup> A-hours), since such capability will be required for a useful MPD thruster,

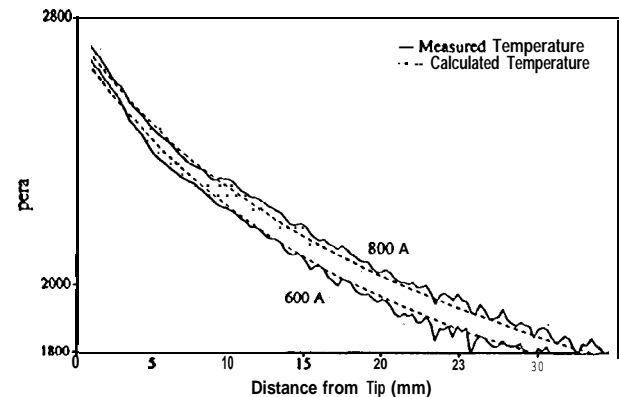


Fig. 5 Comparison of calculated and measured high-current cathode temperatures.

#### NEP System Studies

For challenging exploration and science missions envisioned for the 21st century nuclear electric propulsion (NEP) will be required. Because of its much greater projected performance relative to projected chemical rocket performance NEP enables a number of outer planet orbiter and satellite tour missions. Moreover, NEP provides a large reduction in the initial mass in low Earth Orbit (LEO) and greater flexibility in the launch data to most destinations. The higher on-board power for NEP can also be used to enhance significantly the scientific part of the mission. The critical performance objectives for NEP systems are given in Table 1 [57].

Table 1 NEP Performance Objectives

ITEM	VALUE
Electric Power to Thrusters	50- 100 kW
System Specific Mass	<40 kg/kW
Full Power Lifetime	4 - 8 years
Thruster Lifetime	10,000 hours
Restart Capability	Multiple

Several studies have suggested an evolutionary approach of moving from solar electric propulsion (SEP) to NEP as an affordable way to gain experience with electric propulsion while accomplishing some high-interest inner solar system missions (Fig. 6). NASA is currently pursuing this general approach with strong emphasis implementing the first step (i.e. the use of solar electric propulsion for planetary missions).

## Concluding Remarks

Studies and experiments continue to confirm the promise of electric propulsion to offer significant benefits for a wide range of space missions. As a result, NASA continues to develop a range of technology options to cover near and far-term projected mission needs. Significant progress has begun to appear in the insertion of electric propulsion technologies into operation systems as evidenced by the use of hydrazine arcjets on the Telstar 401 spacecraft, the use of resistojets on numerous communication satellites and the planned use of the plasma contactor on Space Station. After four decades of research, electric propulsion is well positioned to enhance the performance of future spacecraft.

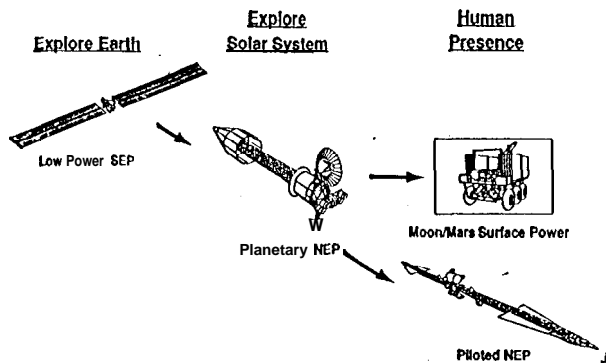


Fig. 6 Evolutionary development strategy from solar electric propulsion (SEP) to nuclear electric propulsion (NEP).

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